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RESEARCH ARTICLE

Operational properties of forestry mulchers for cleaning field protection forest belts after sanitary cuttings

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Abstract

Experimental studies were conducted with forestry mulchers in field protection forest belts and clearings in the North-Eastern region of Bulgaria . Regression models were elaborated to determine the operating performance and fuel consumption of forestry mulchers with a rated power of 70 kW to 245 kW for site preparation of clearings with the amount of wood residues, shoots and bushes from 15 t/ha to 48 t/ha. The mode of influence of the mulcher rotor speed , the concentration of comminuted biomass and the mulching unit power on the performance and fuel consumption were established. When treating clearings with small biomass concentration of 15 t/ha, the productivity of the mulching units with a greater power of 245 kW is 0.392 ha/h, and of those with a smaller power of 70 kW it is 0.086 ha/h. This difference is even greater in clearings with a biomass concentration of 48 t/ha, where the operating productivity of 245 kW mulchers is 0.304 ha/h and that of 70 kW mulchers is 0.021 ha/h. Mulching units with greater power also have a lower relative fuel consumption per unit area. This fact is more pronounced in clearings with a larger amount of wood residues of 48 t/ha, where the fuel consumption of bigger units with a power of 245 kW is 155 l/ha, of units with a medium power of 160 kW it is 217 l /ha, and of units with a smaller power of 70 kW it is 335 l/ha. For treating clearings with relatively less wood residues and shrubs of 15 t/ha, depending on the rated power of mulching units, these fuel costs are respectively 86 l/ha, 122 l/ha and 214 l/ha. The optimal power and rotor revolutions of forestry mulchers when processing cuttings with different concentrations of woody biomass were determined.

Keywords

comminuting, woody biomass, performance, fuel consumption, power, regression models

Introduction

Mulching technologies have indisputable ecological and technological advantages compared to the bulldozer technologies for cleaning forest areas and clearings applied so far in Bulgaria (Marinov 2014; Glushkov et al., 2021). Forestry mulchers are universal brush cutters for cleaning forest areas from undesirable tree and shrub vegetation, for comminuting wood residues from logging, for cleaning fire lines, electrical overhead and underground cables, etc. They have a milling working body that chop the wood into chips that spread evenly over the surface of the land. Depending on the rotor diameter, they can cut and shred trees, shrubs and stumps with a diameter of up to 25-50 cm. Compared to other brush cutters, mulchers have wider technological capabilities (Marinov, 2021a). When operating with mulchers, there is no need to collect and transport the processed wood, which reduces the overall production costs (Jordanova and Marinov, 2015; Löf et al., 2012; Marinov and Jordanova, 2017a;). In addition, the risk of wildfires and development of diseases and pests is reduced (Hallbrook et al., 2006; Fornwalt et al., 2017). The mulchers are suitable for clearing forest areas from wild fires, windstorms, floods and other abiotic damages to the forests (Von der Gönna, 1992; Löf et al., 2016; Smidt et al., 2019). The main disadvantages of mulchers are their limited application into very stony terrain, as well as the higher consumption of energy and fuel, compared to other rotary brush cutters with disc and chain working bodies (Popikov et al., 2011).

From the research carried out with rotary brush cutters and mulchers, it was found that higher rotor revolutions lead to lower energy costs and fuel consumption (Bukhtoyarov et al., 2021; Furmanov et al., 2020; Marinov, 2019a). At working speed of the mulching unit from 0.05 km/h to 1.0 km/h and rotor revolutions of 1000-2000 rpm, the chips thickness is between 1.5 mm and 30 mm (Kostov, 2019a; Marinov and Kostov, 2019). Smaller chips decompose and assimilate faster in the upper soil layer, improving the organic composition and fertility of the soil. To reduce fuel load in high-fire-risk forests, comminuted wood fragments are recommended to be thicker than 3” or 7.62 cm (Fight and Barbour, 2004; Reiner et al., 2009; Fornwalt et al., 2017). Therefore, higher operating speeds of mulching units are recommended in such forests – 2.5-5 km/h. Depending on the rotor diameter and the power of the mulching unit, mulchers can shred stumps and tree stems with a diameter of 15 to 60 cm (FAE, AHWI).

Modern technologies for site preparation for reforestation with forestry mulchers and tillers, were introduced in Bulgaria relatively recently – from 2014. The research carried out so far in Bulgaria for poplar clearings preparation with a self-propelled forestry unit PT-400 and a multitask milling machine FAE 300/S, showed the relatively high technological and operational properties of this type of machine (Jordanova and Marinov, 2015; Marinov et al., 2017; Marinov, 2019b; Marinov and Stefanov, 2019; Marinov, 2021b). The results obtained from the research of Glushkov et al. (2021) and Marinov and Jordanova (2017) establish that compared to the traditional technology with bulldozer units, the new mulching technology is distinguished by higher economic and environmental indicators. Research was also carried out with milling machines for soil preparation of a non-renewed forest area in the lower flat-hilly forest vegetation belt

in Bulgaria. In one of the first studies with such machines, it was found that mulchers have about twice the shift productivity and 30% lower fuel consumption compared to universal bulldozers (Marinov, 2014). The research by Kostov (2019a and 2019b) and Marinov and Kostov (2019) show that, compared to traditional technologies for soil preparation with dozers and plows, milling machines provide higher quality and lower time and labor costs. In the study by Kostov (2019c) of a forestry tiller FAE SSM/HP for soil preparation in clearings with wood residues 36 t/ha, and stumps with diameter 18 cm and density 31 pcs/da, it was established that the cost time of the new technology is 33.8 h/ha, and according to the traditional one – 98.5 h/ha. The average price according to the new technology is 2180 €/ha, and according to the traditional one – 2955 €/h. In a recent research by Marinov and Kostov (2022) on forestry tillers for deep tillage up to 40 cm and shredding of stumps and roots of hard broad-leaved species of different diameter and density, it was established that of all the significant factors, the diameter has the strongest influence on the fuel consumption and performance of the milling machines. In the study of Berude et al. (2021) on the production costs from applying a mulching technology to growing young Scots pine plantations, it was found that, in addition to better economic indicators, higher stand growth was also achieved. Bukhtoyarov et al. (2021) studied the effectiveness of a rotary brush cutter for cleaning shoots and brush up to 3 m in height, and up to 2 cm in diameter, in young forest plantations, establishing that higher rotor speeds resulted in lower energy costs. In the previous research published by Bulgarian and foreign authors on the cleaning of field protection forest belts and clearings in the lower forest vegetation belt of oak forests, the influence of the amount of comminuted wood, the power of the drive unit, and the rotor rotation frequency of the forestry mulchers, have not yet been sufficiently well studied.

The aim of this study is to establish the way the rotor rotation speed, the concentration of woody biomass, and the rated power of the mulching unit, all influence the main operational properties of forestry mulchers for cleaning field protection belts and clearings.

Materials and Methods

The methods of mathematical modeling, regression analysis and planning of the experiment were used. To define the operating conditions, the experimental trial areas method wa s used.

Location and objects of study

The experimental areas with testing polygons are located in the cuttings of field protection forest belts on the territory of the North-East State Forest Enterprise of Shumen. The main tree species are sessile oak, turkey oak, black locust and ash. Accord-

ing to the classification scheme of the habitats in Bulgaria, the experimental areas fall into the Myzian forest vegetation area, in the lower plain-hilly belt, sub-belt of the oak forests – M-I-2, $D_{2,3}$ (Raikov et al. 2011) The terrains are flat to sloping with a slope of 4-10 degrees. The altitude is 220-350 m. The boundary coordinates of the experimental areas are 43°06.42 – 43°99.31 N and 27°21.78 – 28°58.28 E.

The trial areas are located on the territory of the following forestry units and divisions:

- State Forestry of Dobrich: divisions: 145-д1; 190-1; 224-м; 1072-а,-б1;
- State Forestry of Tervel: divisions: 19-б,з; 67-г; 114-д,и,р; 142-б; 318-а;
- State Forestry of Balchik: divisions: 1714-б; 2004-в; 2026-а; 2077-а,б; 2078-а; 2079а; 2104-б; 2189-в; 2365-а,б,в,г; 2799-а; 43-14;
- State Forestry of General Toshevo: divisions: 115-п; 154-и; 1681-а,б; 1790-а;
- State Forestry of Varna: divisions: 246-ж; 1853-а.

The objects of the research are different mulching units for comminuting wood waste, shoots and brushes in clearings and field protection forest belts. The subject of research are the operational properties of the machines, such as operating productivity and relative fuel consumption. The following mulching aggregates were studied:

* Forestry mulcher AHWI 550m with working width B_p = 2.4 m, driving by Fendt 936 Vario tractor with rated power N_{nom} = 243 kW/330 h.p. (Fig. 1A);
* Forestry mulcher FAE SFM 225 with working width B_p = 2.25 m, driving by Fendt 933 Vario tractor with rated power N_{nom} = 221 kW/300 h.p.;
* Forestry mulcher SEPPI M/225 with working width B_p = 2.25 m, driving by Valtra T214 tractor with rated power N_{nom} = 158 kW/215 h.p.;
* Forestry mulcher FAE UML/S/DT 225 with working width B_p = 2.25 m, driving by John Deere 6155R tractor with rated power N_{nom} = 116 kW/155 h.p;
* Forestry mulcher FAE UML/VT 175 with working width B_p = 1.82 m, driving by Bobcat T770 mini track loader with rated power N_{nom} = 69 kW/92 h.p. (Fig. 1B).

Parameters and conditions of the study

Input parameters. Rotor speed is a major factor that can be managed and maintained at different levels when conducting a mixed active-passive experiment with forestry mulchers. The input factors, which during the study cannot be managed, but can be controlled and maintained at certain levels, form the group of unmanaged controlled factors. These factors include the technical indicators of the machines and the working conditions – slope of the terrain, woody species, concentration of the wood biomass, working width, rated power of the unit, technical condition of the machines, etc. Factors that can be held constant at different levels are suitable for conducting passive and active-passive experiments. The controlled input factors are established at levels corresponding to the working conditions in the lower forest vegetation zone of the oak forests in Bulgaria.

A – AHWI 550m forestry mulcher with a Fendt 936 Vario tractor

B – FAE UML/VT 175 forestry mulcher with Bobcat T770 mini track loader

Figure 1. Forestry mulchers for comminuting wood waste, stem and shrubs (Photo by K. Kostov)

The concentration of wood biomass per unit area is a major factor in the study of forestry mulchers. It is defined as the sum of the remaining wood residue mass – branches, tree tops and defective wood, and the mass of standing vegetation – trees and shrubs. This mass can be measured and established in any experimental area. To establish the amount of mulched woody mass per unit area, the method of the trial sites, in which control samples are composed, is used. For this purpose, on an area of 1 decare, 25 trial sites with dimensions of 2x2 m were set evenly. The number of trial sites is such that their total area should cover 10% of the overall experimental area. At each site, control samples of mulched wood chips are drawn up and weighed on site. The mean wood biomass in each plot was determined as an average weighted value.

The rotor rotation speed as a managed factor is studied in the range of 500 min^{-1} to 1000 min^{-1}. It is good that this factor has a larger variation interval, which will reduce the probability of obtaining inadequate models, and confounding factors will have a less significant influence on the accuracy of the obtained results (Vuchkov and Stoyanov, 1986). From preliminary trials, it was found that at lower rotor speeds, relative fuel consumption was greater and performance was lower. For this reason, the lower level of this factor is assumed to be 500 min^{-1} and the upper level to be at the maximum rotor revolutions of 1000 min^{-1}.

Output parameters. The initial parameters Y_j were chosen in accordance with the purpose of the study and express the main operating properties of the mulchers. The following indicators were studied as such parameters: Y_1 – operating hourly productivity, W_h [da/h]; Y_2 – relative fuel consumption, G_o [l/da]. The operating productivity Y_1 is determined by the duration of the process and mulching area by the formula,

$$W_h = Y_1 = \frac{F}{t}, \text{ da/h} \qquad (1)$$

Where *F* is the mulching area, da; *t* is the duration of the process, h.

The relative fuel consumption Y_2 is an essential indicator of the operating properties of forestry mulchers and has a major weight in determining the cost of site preparation. It is used as the main operating criteria for finding optimal technological solutions (Marinov, 2021). The relative fuel consumption is expressed by the amount of fuel that is consumed per unit of mulched area, Q

$$G_o = Y_2 = \frac{Q}{F}, \text{ l/dka,} \tag{2}$$

Where *Q* is the amount of the fuel consumed, l.

The mass of the mulched materials is measured with an electronic "Kern" scale, with an accuracy of 1 g. The fuel consumed is determined by the on-board computer of the tractors. An electronic stopwatch with an accuracy of 0.1 sec is used to measure the time of the operations. Garmin-550 GPS is used to measure areas. To measure linear dimensions, a Bosch GLM 80 laser tape measure is used, with a range of up to 80 m and an accuracy of ±1 mm, and a Yucon Extend LRS-1000 laser rangefinder, with a range of up to 1000 m and an accuracy of ±1 m.

Design of experiments (DOE)

From the studies carried out so far with forestry milling brush cutters in poplar cuttings, it was established that the obtained dependencies for determining the relative fuel consumption, as functions of the response of the input factors, are described by second-order polynomials

(Marinov 2019b). Active-passive and passive experiments with two input factors are designed to determine the influence of the rated power of the mulching unit, the concentration of the mulching wood biomass and the rotor speed.

Design of a two-factor active-passive experiment. It is used to establish the joint impact of the rotor speed and wood biomass concentration on the operating productivity and relative fuel consumption of forestry mulchers. The first factor rotor rotation frequency is actively managed, while the second factor wood biomass concentration is maintained at several levels. The study was conducted with an AHWI 550m forestry mulcher driven by a Fendt 936 Vario tractor.

The input factors and variation levels have the following notations and levels:

X_1 is the rotor rotation frequency: 5 levels of variation: 500, 625, 750, 875 and 1000 min^{-1}.

X_2 is the concentration of mulched woody mass: 4 levels of variation: 15, 25, 36 and 48 t/ha.

The unmanaged input factors that are kept at one level are: rated power of the mulching unit $N_{ном}$ = 243 kW; working width B = 2.4 m; wood species – turkey oak, sessile oak, black locust and ash; terrain slope 4-8 degrees.

The design of a complete two-factor active-passive experiment to determine the influence of rotor speed and woody biomass concentration on the operating productivity and fuel consumption of an AHWI 550m forestry mulcher driven by a Fendt 936 tractor is given in Table 1. To carry out the calculation procedures, the natural values are replaced by coded ones.

Design of a two-factor passive experiment. This experiment aims to establish the joint influence of the rated power of the mulching units and the concentration of the woody biomass on the operating properties of the mulchers. The study is conducted with mulching units mentioned above. The experimental areas are located in clearings with a woody biomass concentration of 15 t/ha, 25 t/ha, 36 t/ha and 48 t/ha. The other input factors, such as wood species of the mulched wood, working width, terrain slope, etc., are kept at constant levels.

The controlled input factors and their levels of variation are:

X_1 – rated power of the mulching unit: 5 levels of variation: 69, 116, 158, 221 and 243 kW.

X_2 – concentration of wood mass per hectare: 4 levels of variation: 15, 25, 36 and 48 t/ha.

The design of a complete two-factor passive experiment with forestry mulching units of different rated power is given in Table 1.

Table 1. Design of experiments

№ of exp.	Active-passive experiment				Passive experiment				Output parameters	
	Input factors									
	Natural form		Coded form		Natural form		Coded form		Operating productivity	Relative fuel consumption
	X_1 min^{-1}	X2 t/ha	X_1	X2	X_1 kW	X2 t/ha	X_1	X2	Y_1 da/h	Y_2 l/da
1	500	15	-1	-1	69	15	-1	-1	Y1,i,j	Y2,i,j
2	625	15	-0.5	-1	116	15	-0.460	-1	……	……
3	750	15	0	-1	158	15	0.023	-1	……	……
4	875	15	0.5	-1	221	15	0.747	-1	……	……
5	1000	15	1	-1	243	15	1	-1	……	……
6	500	25	-1	-0.394	69	25	-1	-0.394	……	……
7	625	25	-0.5	-0.394	116	25	-0.460	-0.394	……	……
8	750	25	0	-0.394	158	25	0.023	-0.394	……	……
9	875	25	0.5	-0.394	221	25	0.747	-0.394	……	……
10	1000	25	1	-0.394	243	25	1	-0.394	Y1,i,j	Y2,i,j
11	500	36	-1	0.273	69	36	-1	0.273	……	……
12	625	36	-0.5	0.273	116	36	-0.460	0.273	……	……
13	750	36	0	0.273	158	36	0.023	0.273	……	……
14	875	36	0.5	0.273	221	36	0.747	0.273	……	……
15	1000	36	1	0.273	243	36	1	0.273	……	……
16	500	48	-1	1	69	48	-1	1	……	……
17	625	48	-0.5	1	116	48	-0.460	1	……	……
18	750	48	0	1	158	48	0.023	1	……	……
19	875	48	0.5	1	221	48	0.747	1	……	……
20	1000	48	1	1	243	48	1	1	……	……

From the research carried out so far in Bulgaria with a self-propelled unit PT-400 with a multifunctional forestry milling machine FAE 300/S for soil preparation of poplar clearings (Marinov, 2019b), it was established that the models of the studied parameters, are described by second-order polynomials. For this reason, the same hypothesis is assumed here as well, that the regression models for operating productivity and fuel consumption, as a functions of response, are described by second-order polynomials, according to the following relationship:

$$\hat{y} = b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i<j} b_{ij} x_i x_j + \sum_{i=1}^{m} b_{ii} x_i^2 \qquad (3)$$

Where $-1 \leq x_i \leq 1$ are the coded values input factors, $i = 1,2,\ldots,m$; $m = 2$ are the number of input factors; b_0 is the regression coefficient of the free term; b_i are the regression coefficients of the linear terms; b_{ij} are the regression coefficients of the interaction between the linear terms; b_{ii} are the regression coefficients of squared terms.

Regression coefficients are estimated at a significance level of $\alpha = 0.05$. The adequacy of the obtained regression models is performed by evaluating the significance of the multiple correlation coefficient R (Vuchkov and Stoyanov, 1986). For these models to be usable, the multiple correlation coefficient R should be as close as possible to 1.0. In addition to the R coefficient, the quality of the regression models is also assessed by the F-criteria. The condition for significance of the coefficient R is checked according to the following criteria:

- If the condition $F > F_{table}(\alpha,\nu_1,\nu_2)$ is met , then the multiple correlation coefficient R is significant, the model is adequate and can be used to predict the studied parameters;
- If the inequality $F \leq F_{table}(\alpha,\nu_1,\nu_2)$ is met, then the multiple correlation coefficient R is insignificant and the model is inadequate. This may be due to incorrect selection of a lower order model or the presence of other strongly influencing factors not included in the model sought.

Optimization

Optimization can be carried out with an operational criterion (Marinov, 2021). For this purpose, single-objective optimization is used to find the minimum value of the relative fuel consumption. From the previous studies with multitask forestry milling machines in poplar clearings it was found that the single-objective optimization with the gradient algorithm method gave optimal solutions, which did not differ significantly from those with multi-objective optimization, where operating productivity is used as the second objective function (Marinov, 2019b; Marinov and Kostov, 2022). Optimization is performed after establishing adequate regression models for the relative fuel consumption function. It is carried out using the method of the gradient algorithm, in which the minimum of the function y_2 is sought,

$$\hat{y}_2 \rightarrow \min. \qquad (4)$$

Results and discussion

The research was carried out in the period 2019-2021. Active-passive and passive experiments were conducted in accordance with the research methodology.

Results and analysis of the two-factor active-passive experiment

This experiment was conducted with an AHWI 550m forestry mulcher driven by a Fendt 936 Vario tractor with rated power of 220 kW. The first managed input factor X1 – rotor rotation frequency is regulated in the interval from 500 min^{-1} to 1000 min^{-1}, in 125 min^{-1}. The second input factor X_2 – concentration of woody mass in the clearings was established and maintained at levels of 15 t/ha, 25 t/ha, 36 t/ha and 48 t/ha. The obtained results were used to elaborate regression models and to conduct single-objective optimization to establish the optimal rotor speed. The experimental results obtained for the output parameters Y_1 – operating productivity and Y_2 – relative fuel consumption are given in Table 2.

Table. 2. Results of the active-passive experiment with an AHWI 550m forestry mulcher

№ of exp.	Input factors				Output parameters from experiments		Output parameters from regression models	
	Natural form		Coded form		Operating productivity	Relative fuel consumption	Operating productivity	Relative fuel consumption
	X_1 min^{-1}	X2 t/ha	X_1	X2	Y_1 da/h	Y_2 l/da	y_1 da/h	y_2 l/da
1	500	15	-1	-1	2.93	16.65	2.91853921	16.53485046
2	625	15	-0.5	-1	3.19	13.58	3.183936555	13.57718643
3	750	15	0	-1	3.42	11.22	3.41790533	11.2227367
4	875	15	0.5	-1	3.61	9.37	3.620445535	9.47150127
5	1000	15	1	-1	3.79	8.25	3.79155717	8.32348014
6	500	25	-1	-0.394	2.84	17.59	2.858796039	17.48084187
7	625	25	-0.5	-0.394	3.09	14.52	3.105912155	14.62384513
8	750	25	0	-0.394	3.33	12.35	3.321599701	12.37006268
9	875	25	0.5	-0.394	3.51	10.69	3.505858677	10.71949454
10	1000	25	1	-0.394	3.66	9.88	3.658689082	9.67214069
11	500	36	-1	0.273	2.71	19.18	2.717060451	19.43583415
12	625	36	-0.5	0.273	2.95	16.62	2.944055147	16.68963786
13	750	36	0	0.273	3.16	14.56	3.139621274	14.54665587
14	875	36	0.5	0.273	3.31	13.11	3.303758831	13.00688819
15	1000	36	1	0.273	3.43	12.13	3.436467818	12.0703348
16	500	48	-1	1	2.49	22.72	2.47189021	22.65733254
17	625	48	-0.5	1	2.67	20.13	2.676953465	20.03190377
18	750	48	0	1	2.83	18.05	2.85058815	18.0096893
19	875	48	0.5	1	2.99	16.65	2.992794265	16.59068913
20	1000	48	1	1	3.11	15.56	3.10357181	15.77490326

The obtained experimental results were subjected to statistical processing with the computational program for regression analysis QstatLab. After stepwise analysis and exclusion of non-significant regression coefficients, adequate models were obtained. To determine the operating productivity $\hat{y}_1$ and relative fuel consumption $\hat{y}_2$, as functions of the response to the input factors X_1 and X_2, the following regression models were obtained:

$$\hat{y}_1 = 3.2238 + 0.3763X_1 - 0.2837X_2 - 0.0629X_1X_1 - 0.0895X_2X_2 - 0.06039X_1X_2, \quad (5)$$
$$\hat{y}_2 = 13.54 - 3.7735X_1 + 3.3935X_2 + 1.2064X_1X_1 + 1.0762X_2X_2 + 0.3323X_1X_2, \quad (6)$$

To assess the adequacy of the obtained models in equations (5) and (6) and their suitability for predicting the output parameters, according to the accepted methodology, the coefficient for multiple correlation R and F-criterion of the Fisher distribution were used. The obtained results of the variance analysis for evaluating the quality of the models $\hat{y}_i$ are given in Table 3.

Table 3. ANOVA analysis of $\hat{y}_i$ functions of response from active-passive experiments

ANOVA					
Source	**Sum of squares**	**Degrees of freedom**	**Mean squared error**	**F**	**P**
	$\hat{y}_1$ – operating productivity, da/h				
Model	2.39677	5	0.47935	2784.00027	1.838E-20
Residual	0.00241	14	0.00017		
Total	2.39918	19			
T(0.025,14)= 2.14479; F(0.050,5,14)=2.95825; Residual CKO= 0.013122; R-sq=0.999; Radj-sq=0.99864; PRESS = 0.00576; R-sq(pred)=0.9976					
	$\hat{y}_2$ – relative fuel consumption, l/da				
Model	282.56099	5	56.51220	3220.05895	6.6446E-21
Residual	0.24570	14	0.01755		
Total	282.80669	19			
T(0.025,14)= 2.14479; F(0.050,5,14)=2.95825; Residual CKO= 0.13248; R-sq=0.99913; Radj-sq=0.99882; PRESS = 0.67850; R-sq(pred)=0.9985					

The results of the analysis of variance show that the multiple correlation coefficients *R* of the two models are significant. From these results, it can be seen that the *F*-criterion values are greater than the tabular ones determined at the corresponding degrees of freedom, with the condition $F > F_{table}(\alpha,\nu_1,\nu_2)$. The squares of the coefficients of multiple correlation R^2 are close to being equal (for $y_1 \rightarrow R\text{-sq} = 0.999$ and for $y_2 \rightarrow R\text{-sq} = 0.99913$), which means that according to the principles of variance analysis, all significant influences in the studied process were taken into account. The squares of the coefficients of determination of the predicted *R*-sq (pred) values also have high values. The estimate for operating productivity is *R*-sq (pred) = 0.9976 and for fuel consumption is *R*-sq (pred) = 0.9985. This means that in the confidence inter-

val 0.95, the obtained regression models predict the mulching process with sufficiently high accuracy. From the conducted statistical analysis, it can be concluded that the proposed regression models in equations (5) and (6) are adequate and describe the studied output parameters with sufficiently high accuracy. They can be used to determine the operating productivity and relative fuel consumption of forestry mulchers with rated power of 220 kW in the studied interval of variation of the input factors X_1 и X_2. The calculated values of the output parameters y_1 and y_2 obtained from regression models are given in Table 2. From these models, graphs were plotted in figure 2 and figure 3 depicting the variation of operating productivity and fuel consumption as a function of rotor speed revolutions and woody biomass concentration.

The obtained results show that both studied factors have a strong influence on the operational properties of forestry mulchers. Regardless of woody mass concentration, an increase in rotor speed leads to an increase in productivity and a decrease in relative fuel consumption. As the amount of mulched wood mass increases, productivity naturally decreases, and fuel consumption per unit area increases, but the dynamics of this change are different. The obtained results show that the influence of woody mass is weaker in clearings with a concentration of up to 20-25 t/ha, while in those with a biomass concentration of more than 30-35 t/ha, this influence is more pronounced. For example, at a rotor speed of 500 rpm, the relative fuel consumption in cuttings with biomass from 15 t/ha to 25 t/ha increases from 16.5 l/da to 17.5 l/da, which is about 1.0 l/ da more, while in cuttings with larger amounts of woody biomass from 36 t/h to 48 t/ha, this consumption increases from 19.4 l/da to 22.7 l/

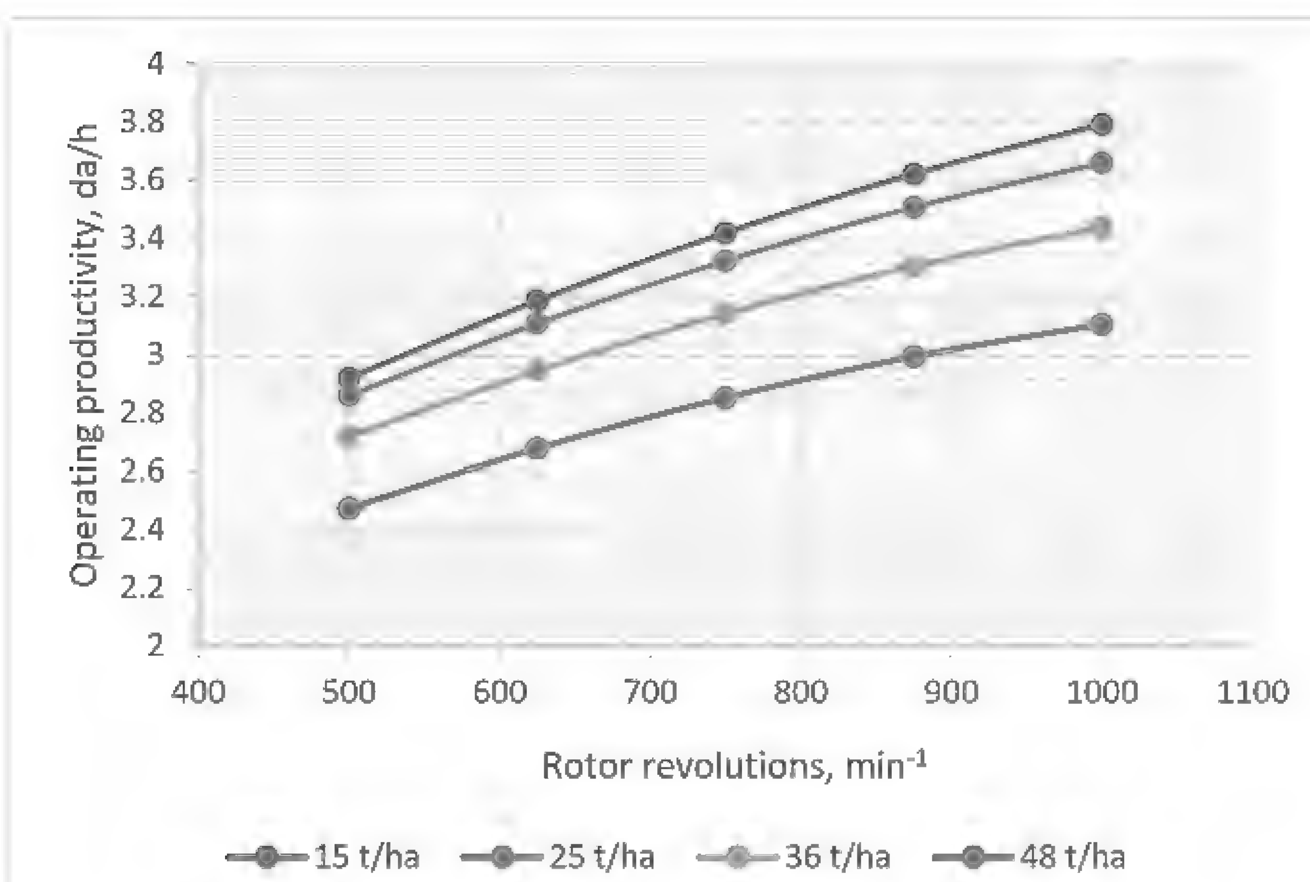

Figure 2. Variation of the operational performance of an AHWI 550 forestry mulcher depending on the rotor revolutions and the concentration of woody biomass

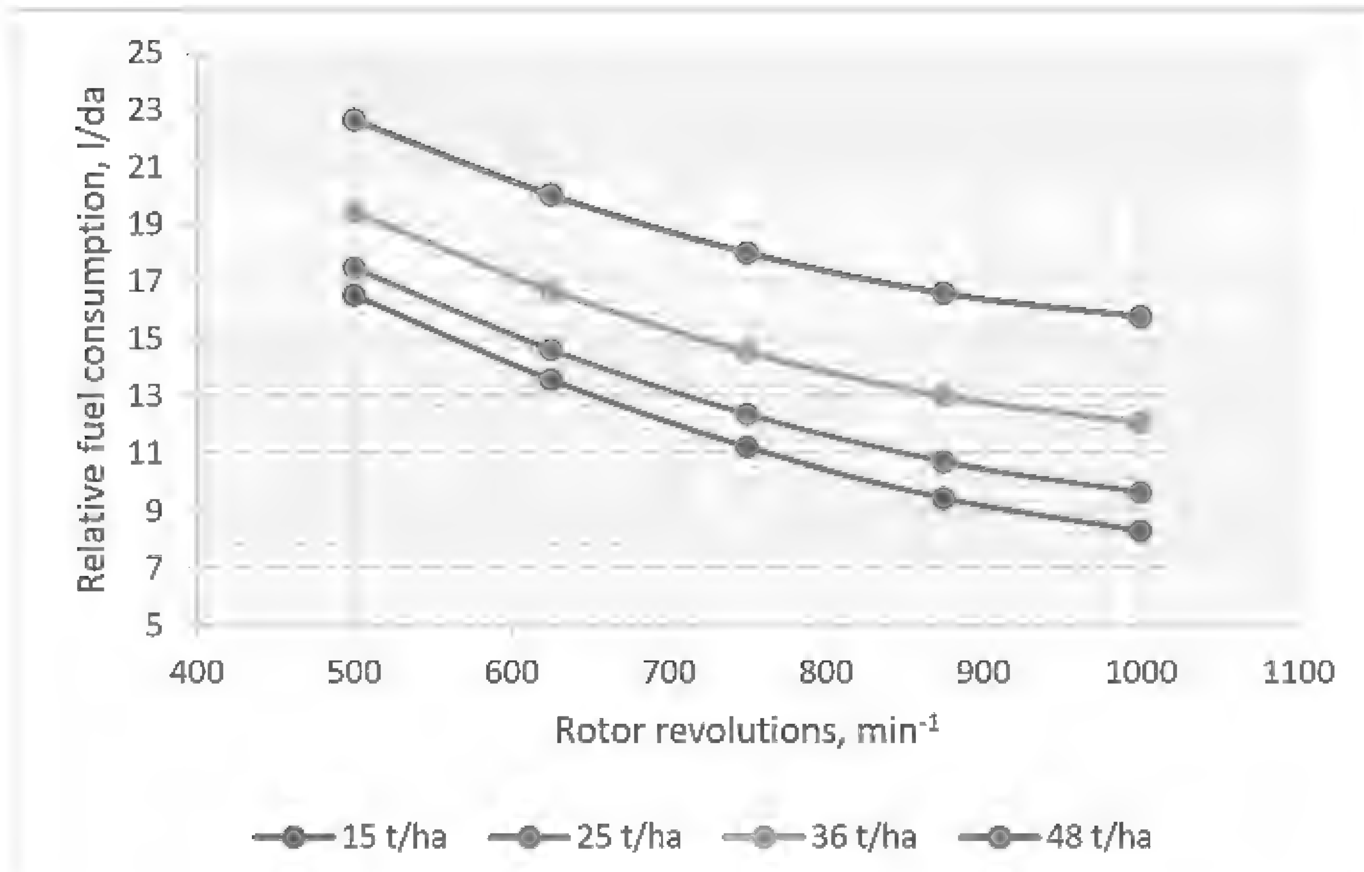

Figure 3. Variation of the relative fuel consumption of an AHWI 550 forestry mulcher depending on the rotor revolutions and the concentration of woody biomass

da, which is about 3.3 l/da more, or almost 3.3 times. At the same levels of woody biomass concentrations, but at a maximum rotor speed of 1000 rpm, the relative fuel consumption increases from 8.3 l/da to 9.7 l/da, which is 1.4 l/da more and from 12.1 to 15.8 l/da, which is 3.7 l/da more, or almost 2.7 times. From the graph in Figure 4, it can be seen that as the rotor speed increases from 500 rpm to 1000 rpm, the slope of the relative fuel consumption curve decreases and towards the end the influence of this factor begins to weaken, but nevertheless it is seen that it has not yet reached its minimum. The evolution of the curve outside the studied factor space indicates that the fuel consumption will continue to decrease until about 1500-2000 rpm. Regarding the operating productivity, depicted in the graph in figure 3, it can be seen that its curve develops relatively more smoothly and with a smaller drop until reaching the maximum rotor speed of 1000 rpm. Here it is seen that the performance will continue to increase at a speed above 1500-2000 rpm. Such an increase in speed is likely to lead to an increase in fuel consumption and to greater dynamic loads in the working bodies and transmission of the mulchers. However, further studies with higher rotor revolutions above 1000 rpm are needed to confirm these hypotheses.

According to the optimization methodology, i n order to determine the optimal rotor revolutions in the studied range from 500 to 1000 rpm, it is necessary to find the minimum of the relative fuel consumption of the mulching unit for cleaning clearings with different concentrations of woody biomass. For this purpose, the area is sought in which the response surface of the objective function y_2 will acquire a minimum value. The optimization is carried out according to the method of the gradient

algorithm, by setting different values of the controllable factor X_1 – rotor rotation frequency, with established constant levels of the factor X_2 – concentration of woody biomass from 15 t/ha to 48 t/ha. The calculations continue until the minimum value of the objective function $\hat{y}_2$ is found. QstatLab software is used for the calculation procedures. After processing the results and finding the minimum of the function y_2, optimal solutions for the variable X_1 were obtained at the basic, upper and lower levels of the factor X_2. The obtained optimal solutions are given in Table 4.

The results show that the relative fuel consumption of the mulching unit is the

Table 4. Results of the single-objective optimization to find the optimal rotor speed

Method: Gradient algorithm (GRAD); --> regression model. $\hat{y}_2$ (MIN); Iterations: 5000;

Variable X_1, min^{-1}: X_1 Range [-1…1]. Variable X_2, t/ha: X_2 = const = 0 = basic level

*** **Optimal solution:**

OBJ1 --> regression model Y_2

No	VAR1	VAR2	OBJ1	Optimum
48	1.0000	0.0000	10.9730	10.97
	1000 min^{-1}	31.5 t/ha		10.97 l/da

Variable X_1, min^{-1}: X_1 Range: [-1…1 Variable X_2, t/ha: X_2 = const = -1 = lower level

*** **Optimal solution:**

OBJ1 --> regression model $\hat{y}_2$

No	VAR1	VAR2	OBJ1	Optimum
58	1.0000	-1.0000	8.3235	8.32
	1000 min^{-1}	15 t/ha		8.32 l/da

Variable X_1, min^{-1}: X_1 Range: [-1…1] Variable X_2, t/ha: X_2 = const = 1 = upper level

*** **Optimal solution:**

OBJ1 --> regression model $\hat{y}_2$

No	VAR1	VAR2	OBJ1	Optimum
30	1.0000	1.0000	15.7749	15.77
	1000 min^{-1}	48 t/ha		15.77 l/da

smallest at the maximum speed of the rotor 1000 min^{-1} and the upper level of the factor $X_1 = 1$. This speed is optimal for all levels of wood mass concentration. At the minimum concentration 15 t/ha and upper level of the input factor $X_2 = -1$, the function y_2 for the relative fuel consumption is $G_o = 10.97$ l/da. At wood mass concentration 31.5 t/ha and basic level of factor $X_2 = 0$, fuel consumption is $G_o = 8.32$ l/da, at 48 t/ha and upper level of factor $X_2 = 1$, this consumption reaches to $G_o = 15.77$ l/da. At this speed, the maximum performance of the mulcher has been established. At a lower level of X_2 and a minimum concentration of wood mass, the operating productivity naturally is the highest $W_h = 3.792$ da/h, at a basic level $X_2 = 0$ it is $W_h = 3.537$ da/h and at an upper level $X_2 = 1$ the productivity is the smallest $W_h = 3.103$ da/h.

With a rotor diameter 550 mm of an AWHI 550m mulcher and an optimal rotor revolutions 1000 rpm, the peripheral speed of the working body and cutting speed is equal to $v_o = 28.8$ m/s. At the operating speed of the mulching unit $v_p = 1.5$ km/h, the kinematic index of milling is $\lambda = 68.5$.

The graphical results for the objective function surface y_2 and the diagram of lines with constant values of the relative fuel consumption of the AHWI 550m forestry mulcher with a Fendt 936 Vario tractor are depicted in Figure 4.

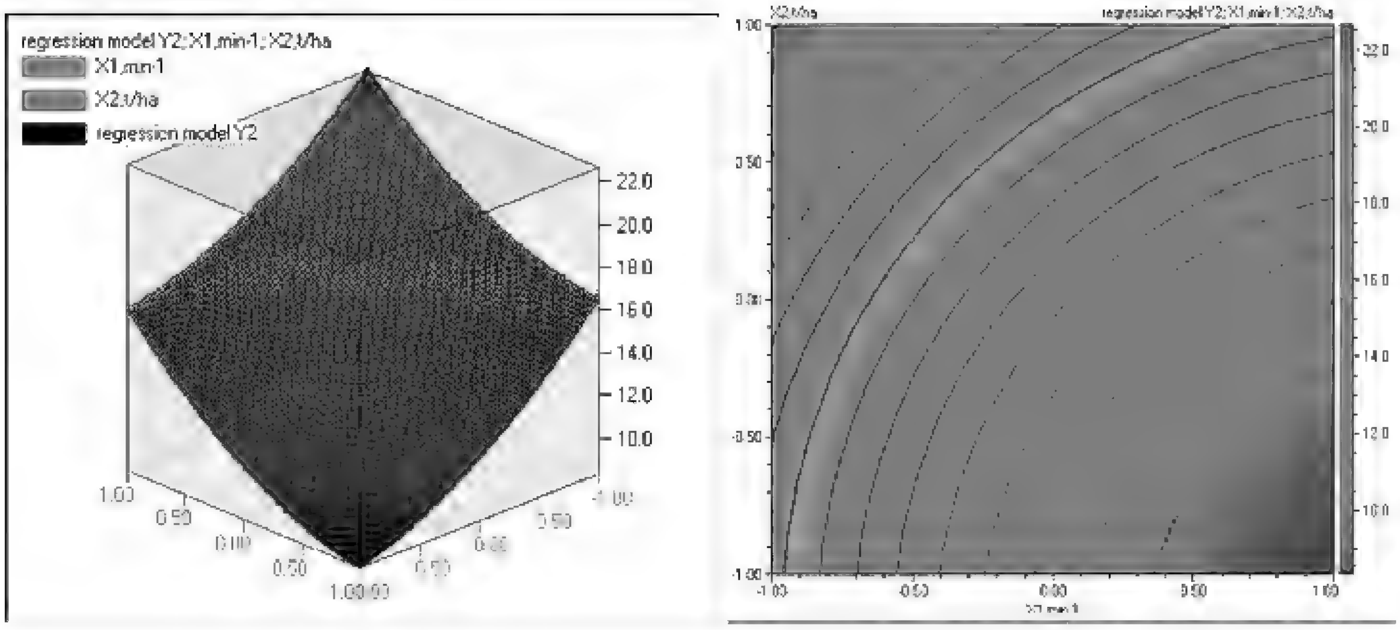

Figure 4. Surface of the objective function y2 and diagram of lines with constant values of relative fuel consumption of AHWI 550 forestry mulcher with Fendt 936 Vario tractor

Results and analysis of the two-factor passive experiment

The first input factor X_1 rated the power of the mulching unit, and is established and maintained at 5 levels in the interval from 69 kW to 243 kW. The second factor X_2 – concentration of woody biomass, like the active-passive experiment, is maintained at 4 levels – 15 t/ha, 25 t/ha, 36 t/ha and 48 t/ha. From the optimization carried out in the previous active-passive experiment, an optimal rotor revolution of 1000 rpm was established. For this reason, in this experiment the rotor speed is kept constant at an optimal value of 1000 rpm. The obtained experimental results for operating productivity Y_1 , and relative fuel consumption Y_2 of mulching units of different power when working in clearings with different concentrations of woody biomass, are given in Table 5.

The obtained results of the experimental observations were subjected to statistical processing with the QstatLab regression analysis program. After a stepwise analysis to determine the significance of the regression coefficients b_i, b_{ij} and b_{ii} at a significance level of $\alpha = 0.05$, the following regression models were obtained to determine the operating productivity and relative fuel consumption as functions of the response of the input factors X1 and X2:

$$\hat{y}1 = 2.409 + 1.474X1 - 0.383X2 - 0.334X1X1 - 0.065X2X2 - 0.057X1X2, \quad (7)$$

$$\hat{y}_2 = 15.956 - 7.710X_1 + 4.772X_2 + 2.631X_1X_1 + 1.169X_2X_2 - 1.315X_1X_2 \quad (8)$$

The adequacy of the obtained models and their suitability for predicting the output quantities $\hat{y}_1$ и $\hat{y}_2$ were evaluated by means of the multiple correlation coefficient R and the F test. The obtained results of variance analysis of the models $\hat{y}_i$ are given in Table 6.

Table 5. Results of the 2-factor passive experiment

№ of exp	Input factors				Output parameters from experiments		Output parameters from regression models	
	Natural form		Coded form		Operating productivity	Relative fuel consumption	Operating productivity	Relative fuel consumption
	X_1 kW	X2 t/ha	X_1	X2	Y_1 da/h	Y_2 l/da	y_1 da/h	y_2 l/da
1	69	15	-1	-1	0.862	21.21	0.86176255	21.3794047
2	116	15	-0.46	-1	1.946	15.95	1.952215745	15.85230676
3	158	15	0.023	-1	2.808	12.53	2.762271362	12.20858162
4	221	15	0.747	-1	3.687	8.84	3.684181333	9.045834986
5	243	15	1	-1	3.914	8.32	3.92365107	8.5909323
6	69	25	-1	-0.394	0.685	24.05	0.719059813	24.08020386
7	116	25	-0.46	-0.394	1.768	18.38	1.790757162	18.12265151
8	158	25	0.023	-0.394	2.603	14.34	2.584036717	14.09390881
9	221	25	0.747	-0.394	3.464	10.42	3.480799962	10.35403442
10	243	25	1	-0.394	3.676	9.78	3.711482238	9.69745587
11	69	36	-1	0.273	0.525	27.75	0.506776942	28.04583298
12	116	36	-0.46	0.273	1.551	21.12	1.557830481	21.61449666
13	158	36	0.023	0.273	2.365	17.21	2.332645295	17.16198051
14	221	36	0.747	0.273	3.232	12.74	3.201730542	12.78688464
15	243	36	1	0.273	3.431	12.13	3.42274081	11.90832952
16	69	48	-1	1	0.258	34.15	0.20949515	33.5533529
17	116	48	-0.46	1	1.184	26.35	1.238047864	26.60561335
18	158	48	0.023	1	1.957	21.56	1.99273694	21.69120321
19	221	48	0.747	1	2.837	16.42	2.831654415	16.62374449
20	243	48	1	1	3.053	15.67	3.04212263	15.5032449

Table 6. ANOVA analysis of $\hat{y}_i$ functions of response from passive experiments

ANOVA					
Source	Sum of squares	Degrees of freedom	Mean squared error	F	P
	$\hat{y}_1$ – operating productivity, da/h				
Model	25.44640	5	5.08928	4776.22892	4.2164E-22
Residual	0.01492	14	0.00107		
Total	25.46132	19			
T(0.025,14)= 2.14479; F(0.050,5,14)=2.95825; Residual CKO = 0.032643; R-sq = 0.99941; Radj-sq= 0.9992; PRESS = 0.03618; R-sq(pred) = 0.99858					
	$\hat{y}_2$ – relative fuel consumption, l/da				
Model	908.46414	5	181.69283	1972.26427	2.0454E-19
Residual	1.28974	14	0.09212		
Total	909.75388	19			
T(0.025,14)= 2.14479; F(0.050,5,14)=2.95825; Residual CKO = 0.30352; R-sq = 0.99858; Radj-sq = 99808; PRESS = 3.80057; R-sq(pred) = 0.99582					

The results of the analysis indicate that the multiple correlation coefficients R of both models are significant. From the obtained estimates in Table 6, it can be seen that the calculated values of the F-distribution are greater than the tabular F_{table} (α,ν_1,ν_2) determined at the respective degrees of freedom ν_1 and ν_2, and the condition $F > F_{table}$ (α,ν_1,ν_2). The squares of the multiple correlation coefficients (R-sq) are close to unity, indicating that all significant workflow influences are accounted for. The values of the squares of the coefficients of determination Rsq (pred) of the predicted values also have high values, for the performance it is R-sq (pred) = 0.9986 and for the fuel consumption R-sq (pred) = 0.9958. Therefore, the obtained models in equations (7) and (8) are adequate and with sufficiently high accuracy describe the studied mulching process. From the variance analysis, it can be concluded that the proposed regression models are suitable for determining the operating productivity and fuel consumption of forestry mulching units with a power of 69 kW to 243 kW for cleaning clearings and field protection forest belts with a concentration of wood waste, shoots and bushes from 15 t/ha to 48 t/ha

Output parameters calculated values from the regression models as functions of the response y_1 and y_2 are given in Table 5. From the obtained results, graphical dependencies were drawn in figures 5 and 6, depicting the way the productivity and fuel consumption of forestry mulchers changes depending on the rated power of the unit and the concentration of comminuted wood biomass in clearings and field protective forest belts.

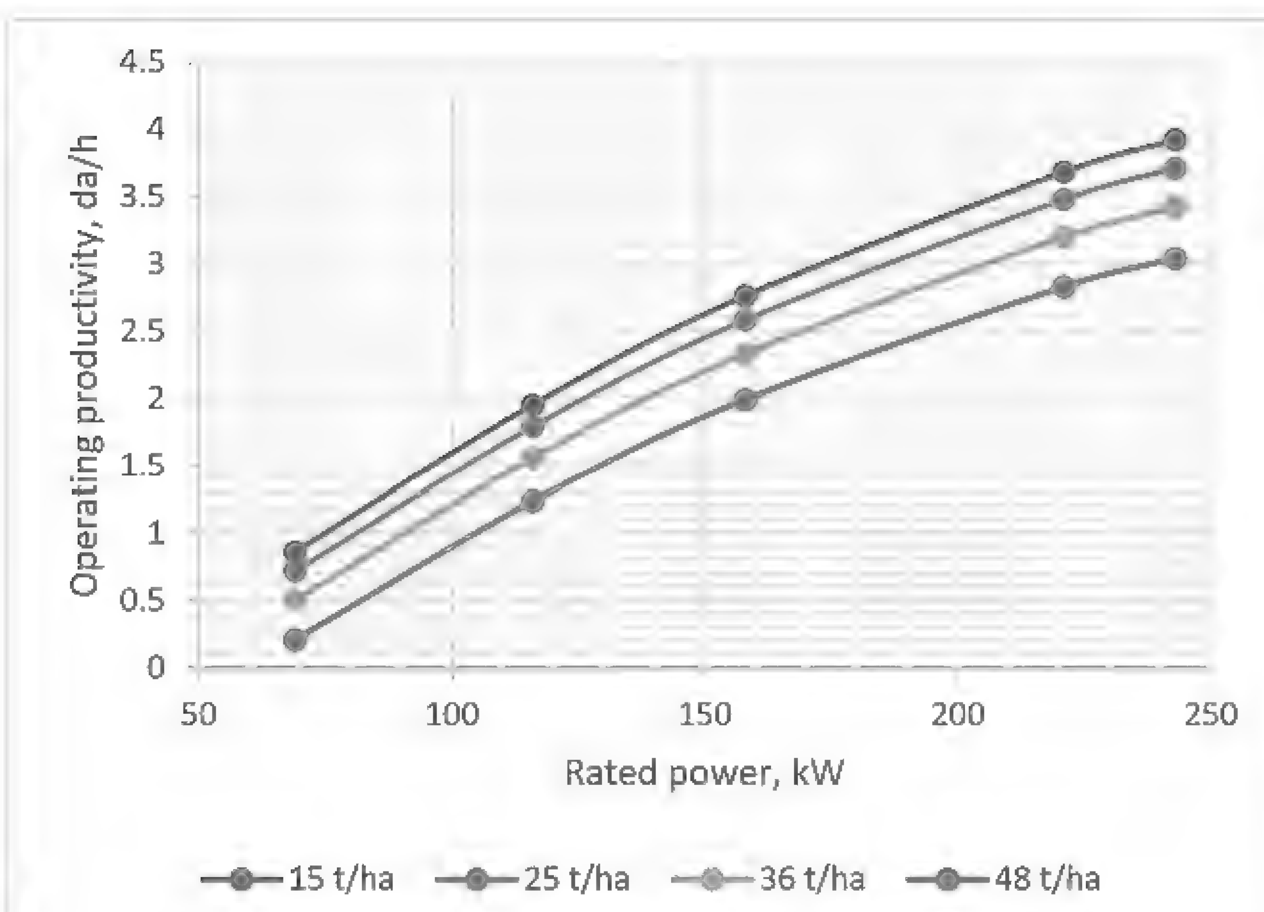

Figure 5. Variation of the operating productivity of forestry mulchers depending on the rated power of the unit and the concentration of comminuted woody biomass

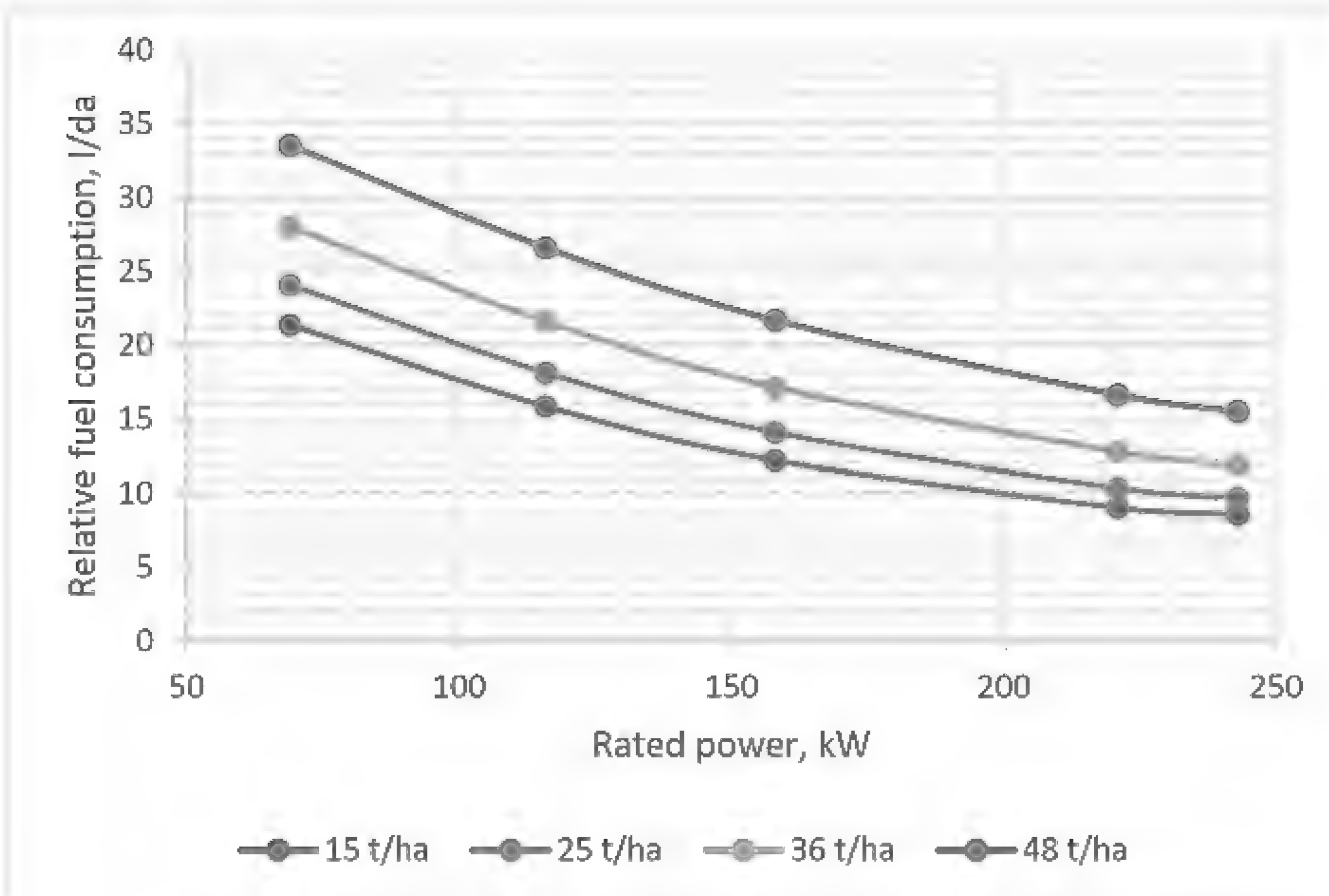

Figure 6. Variation of the relative fuel consumption of forestry mulchers depending on the rated power of the unit and the concentration of comminuted woody biomass

The results indicate that at optimal rotor speed, both factors have a significant impact on the productivity and fuel consumption, but in the studied factor space, the rated power of the mulching units has a greater weight. This influence is particularly pronounced when the rated power of the mulching unit increases to 160 kW, after which its influence begins to weaken. From the graphs in figure 7, it can be seen that this influence is more pronounced on the curve depicting fuel consumption in clearings with a concentration of 15-25 t/ha, and after reaching a value of about 220 kW, the influence of this factor significantly decreases. From the same graphs, it can be seen that when cleaning cuttings with a concentration of wood biomass of 15 t/ha, the minimum relative fuel consumption will be reached at a unit power of about 240-245 kW. When clearing cuttings with 25 t/ha residue mass, the minimum fuel consumption would probably be realized at a power of around 250260 kW. From the graphs in Figure 6, it can be seen that the productivity of the mulching units continues to increase at a high rate even after reaching the upper level of the studied power factor space of 245 kW. From these results it is evident that forestry mulching units with bigger power naturally have higher productivity.

The results of this experiment are used to determine the optimal power of the mulching units for cleaning clearings with different concentrations of woody biomass. The optimization is carried out by the method of the gradient algorithm in accordance with the accepted methodology, where the minimum of the relative fuel consumption is sought – $\hat{y}_2 = G_o \rightarrow \min$. For this purpose, at pre-fixed levels of the

Table 7. Results of the optimization to find the optimal power of the mulching unit

Method: Gradient algorithm (GRAD); --> regression model $\hat{y}_2$ (MIN); Iteration: 5000				
Variable X_1, kW: X_1 Range: [-1..1]; Variable X_2, t/ha: X_2 = const = 0 = basic level				
*** **Optimal solution:**				
OBJ1 --> regression model $\hat{y}_2$				
No	VAR1	VAR2	OBJ1	Optimum
48	1.0000	0.0000	10.8776	10.88
	243 kW	31.5 t/ha		10.88 l/da
Variable X_1, kW: X_1 Range: [-1..1]; Variable X_2, t/ha: X_2 = const = -1 = lower level				
*** **Optimal solution:**				
OBJ1 --> regression model $\hat{y}_2$				
No	VAR1	VAR2	OBJ1	Optimum
58	1.0000	-1.0000	8.5909	8.591
	243 kW	15 t/ha		8.59 l/da
Variable X_1, kW: X_1 Range: [-1..1]; Variable X_2, t/ha: X_2 = const = 1 = upper level				
*** **Optimal solution:**				
OBJ1 --> regression model $\hat{y}_2$				
No	VAR1	VAR2	OBJ1	Optimum
48	1.0000	1.0000	15.5032	15.503
	243 kW	48 t/ha		15.5 l/da

concentration of woody mass X_2, different values of the rated power X_1 were set in the interval from 69 kW to 243 kW. The calculations continue until the minimum value of the objective function $\hat{y}_2$ is found. After processing the results, optimal solutions were obtained for determining the rated power of the mulching unit, with fixed basic, upper and lower levels of the concentration of woody mass. The resulting optimal solutions are given in Table 7.

The obtained optimal solutions for cleaning cuttings and field protection forest belts show that the relative fuel consumption is lower when using mulching units with higher power. Forestry mulchers, driven by tractors with a rated power of 245 kW, are optimal for work in all clearings with a concentration of woody biomass from 15 t/ha to 48 t/ha. The obtained optimal solutions correspond to those obtained in the active-passive experiment at a rotor speed of 1000 rpm. When working with a mulching unit with a power of 245 kW (upper level $X_1 = 1$) and a minimum value of the concentration of 15 t/ha (lower level $X_2 = -1$), the function y_2 for the fuel consumption is equal to G_o = 8.59 l/da. In cuttings with a concentration of woody mass 31.5 t/ha (basic level $X_2 = 0$), the relative fuel consumption is equal to G_o =10.88 l/da, and in those with a concentration of 48 t/ha (upper level $X_2 = 1$) this consumption is G_o = 15.5 l/da. When working with mulching units with a higher power, a higher operating productivity is naturally established. The operating productivity in clearings with a concentration of woody biomass of 15 t/ha ($X_2 = -1$) is W_h = 3.924 da/h, in those with a concentration of 31.5 t/ha ($X_2 = 0$) it is W_h = 3.548 da/h, and in clearings with concentration of 48 t/ha ($X_2 = 1$) it is W_h = 3.042 da/h.

The surface of the objective functions y_2 and y_1 and a diagram of the lines with constant values of the operating productivity, and relative fuel consumption of forestry mulching units of different rated power when cleaning field protection forest belt, and clearings with different concentrations of wood biomass are given in figure 7 and 8.

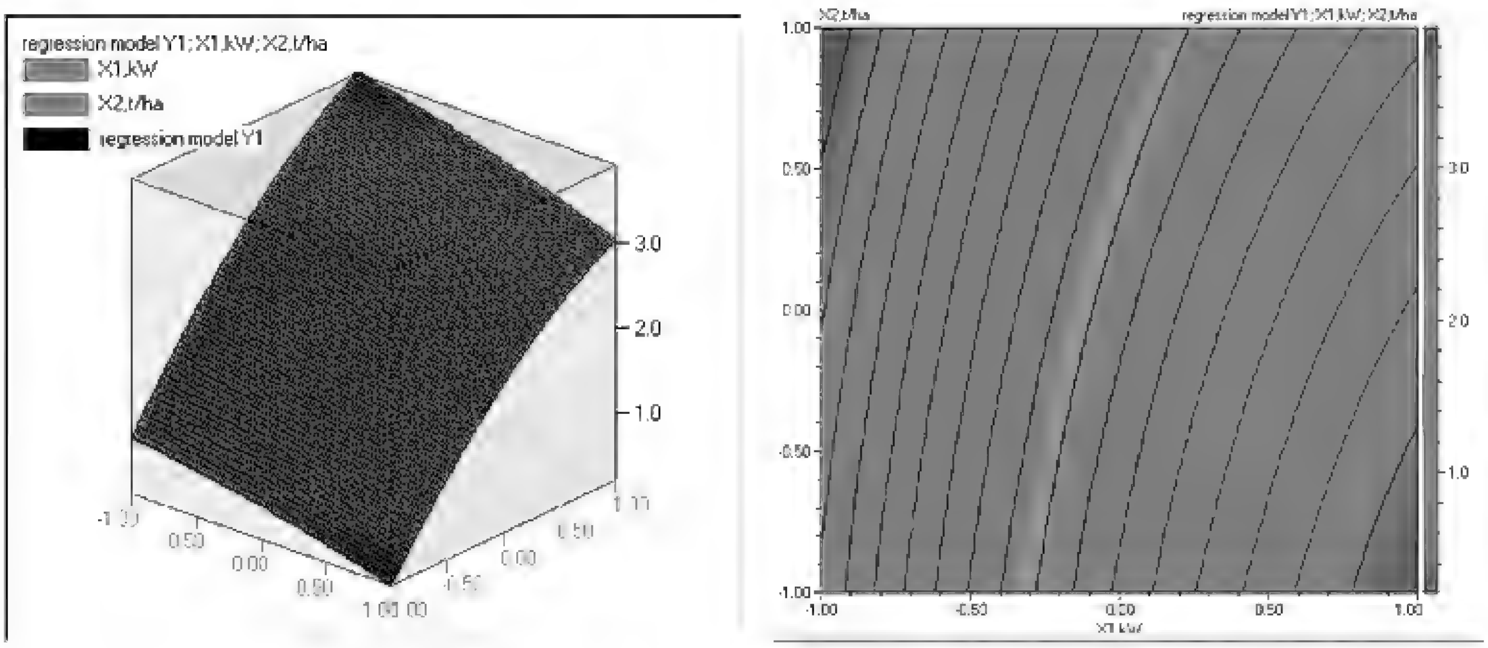

Figure 7. Surface and diagram of the isolines of the objective function y_1 for operating productivity of forestry mulchers with different power in clearings with different biomass concentration

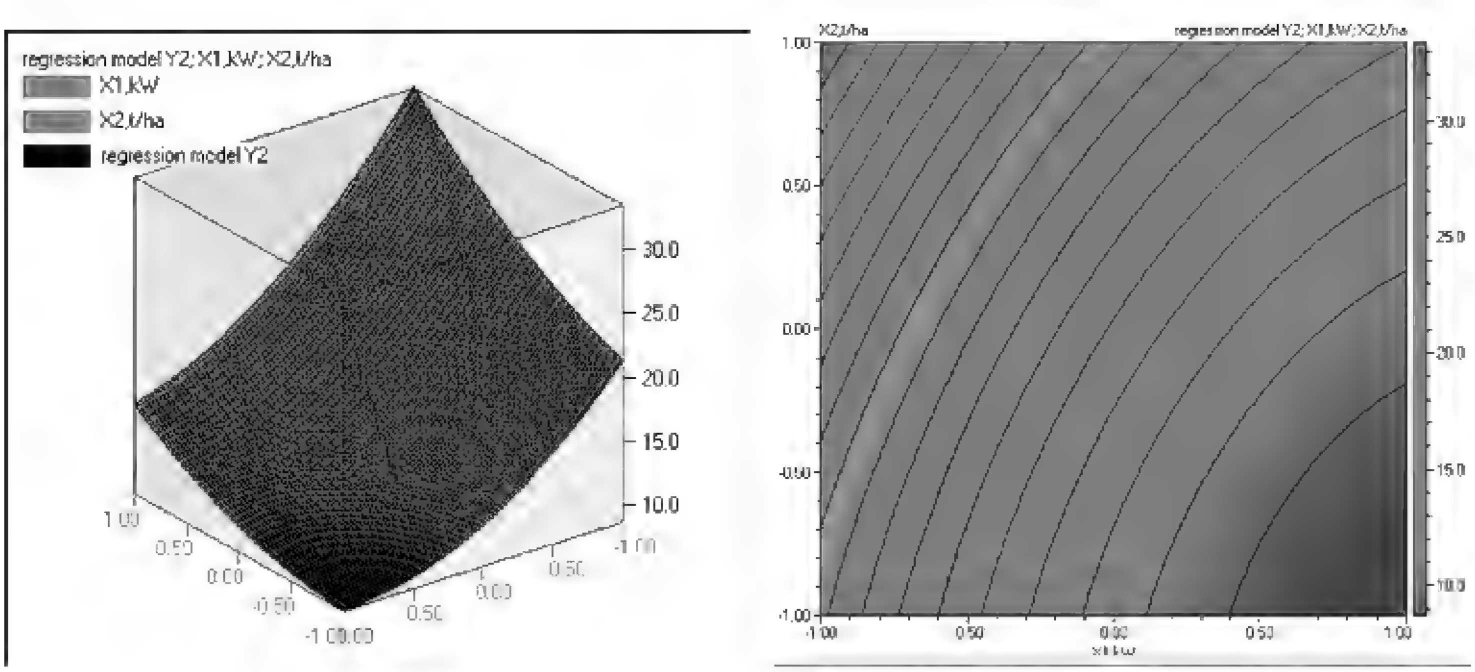

Figure 8. Surface and diagram of the isolines of the objective function y_2 for fuel consumption when operating forestry mulchers with different power in clearings with different biomass concentration

The research that was conducted established that when mulching clearings with wood residues from 15 t/ha to 25 t/ha with a mulching unit with the largest rated power of 245 kW, the relative fuel consumption is the smallest – from 8.6 l/da to 9.7 l/da. When working with a medium power mulching unit of 160 kW in the same clearings, the fuel consumption is from 12.2 l/da to 14.1 l/da, with the excess being 3.6-4.4 l/da. When mulching with a less powerful unit of 70 kW, this consumption is from 21.4 l/da to 24.1 l/da, and the excess is greater – from 12.8 l/da to 14.4 l/da. For cleaning clearings with a larger amount of residues from 36 t/ha to 48 t/

ha, when working with the more powerful 245 kW mulching unit, the relative fuel consumption is from 11.9 l/da to 15.5 l/da. In these clearings, the medium-powered unit has a fuel consumption of 17.2 l/da to 21.7 l/da, with the excess already greater from 5.3 l/da to 6.2 l/da, and the least powerful unit has a consumption of 28.0 l/da to 33.5 l/da, with the excess already more significant from 10.8 l/da to 11.8 l/da. Based on these results, it can be summarized that when mulching clearings with small remaining amounts of wood biomass up to 20 t/ha, the fuel consumption of medium-powered units of 160 kW is higher by about 4 l/da compared to more powerful units with a rated power of 245 kW. If we suppose that the relative costs of materials, amortization and maintenance of a mulching unit (forestry mulcher and tractor) with a power of 160 kW are about 6-7 €/da lower than those of a 245 kW unit, and at current price of diesel fuel 1.5-1.7 €/liter, then the total costs of mulching per unit area will equalize. In cases where these costs turn out to be lower than those mentioned above and the price of fuel is maintained or falls below the above levels, this is likely to reduce the bottom line costs of using medium powered mulching units. However, these assumptions require additional research and analysis of the regional market of this type of machinery in our country, which is still in the process of development. Regardless of the aforementioned hypotheses, mulching units with greater power have higher operating performance. For example, when cleaning forest areas and cuttings with a small amount of wood residue and bushes with a mass of 15 t/ha, the productivity of a mulching unit with a greater power of 245 kW is 3.92 da/h, while for a medium powered unit of 160 kW, it is 2.76 da/h, which is 1.16 da/h or 30% less. When operating with a small power unit of 70 kW, this productivity is 0.86 da/h, which is 3.06 da/h or 78% less. For clearings with more residue 48 t/ha, the productivity of a high power mulching unit of 245 kW is 3.04 da/h, for a medium powered unit of 160 kW it is 1.99 da/h, which is by 1.05 da/h or 35% less, and a unit with less powerful unit of 70 kW it is already 0.21 da/h, which is 2.83 da/h or 93% less. These results show that regardless of the total operation and maintenance costs per unit area, the use of more powerful forestry mulchers will reduce site preparation time

Conclusions

The technological capabilities and operational properties of forestry mulchers depend on the working conditions and technical parameters of the machines. As a result of the conducted research, functional models have been elaborated to determine the operating productivity and relative fuel consumption of mulching units with a rated power of 70 kW to 245 kW for cleaning cuttings from wood residues, shoots and bushes with a concentration of biomass from 15 t/ha to 50 t/ha. The mode of influence of the amount of wood waste, the rotor rotation frequency and the rated power of the mulching unit on the operating productivity and fuel consumption has been established. The optimal rated power and rotor revolutions of mulchers for op-

erating in clearings with different concentrations of wood biomass were determined. As the rotor speed increases from 500 rpm to 1000 rpm, fuel consumption decreases and productivity increases. The relative fuel consumption reaches its minimum at an optimal rotor revolutions of 1000 rpm. To establish how these parameters change beyond the studied speed range, additional research with mulchers having higher rotor speed above 1000 rpm is needed.

Mulching units with higher rated power have lower fuel consumption per decare and higher operating productivity. In clearings with wood mass concentration of 15 t/ha, the productivity of mulchers with a greater power of 245 kW is 3.92 da/h, for those with a medium power of 160 kW it is 2.76 da/h, and for those with a small power of 70 kW – 0.86 da/h. The difference becomes even greater in cuttings with a larger amount of wood mass 48 t/ha, where depending on the rated power of the mulcher, the productivity is respectively equal to 3.04 da/h, 1.99 da/h and 0.21 da/h. Mulching units with a higher power are more economical, i.e. more powerful mulchers have a lower fuel consumption per unit area, regardless of the amount of comminuted biomass. This fact is more pronounced in clearings with a greater amount of wood waste 48 t/ha. In them, the fuel consumption of mulching units with a greater power of 245 kW is 15.5 l/da, for units with a medium power of 160 kW it is 21.7 l/da, and orf those with a small power of 70 kW – 33.5 l/da. In clearings with a smaller amount of wood waste 15 t/ha, depending on the power of the mulching unit, these costs are respectively 8.6 l/da, 12.2 l/da and 21.4 l/da. When mulching such clearings, it is found that the difference in relative fuel consumption between the 245 kW and 160 kW units is a relatively small 3.6 l/da. In order to determine the impact of other running costs on the total costs per unit area, additional economic research and analysis of the regional market for this type of machinery are needed. Regardless of the results of such future research, the use of more powerful forestry mulchers will shorten cuttings preparation times and reforestation deadlines.

The obtained results can be used to develop norms for productivity, time cost and fuel consumption of forestry mulchers for operating in the North-Eastern State Forestry in Bulgaria.

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